BECCS: a threat to energy security?

BECCS

Current electricity mix

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The energy return on investment of BECCS: is BECCS a threat to energy security?

Bioenergy with Carbon Capture and Storage (BECCS) is broadly considered vital to meeting climate change goals. Implicit in these scenarios is the assumption that BECCS simultaneously removes CO_2 from the atmosphere and is a net producer of energy. In this contribution, we evaluate the energy return on investment (EROI) of an archetypal BECCS facility, and identify the conditions under which BECCS is energy positive, and when it is not.

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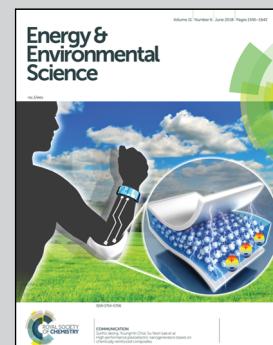
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The energy return on investment of BECCS: is BECCS a threat to energy security?

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Compliance with long term climate targets whilst maintaining energy security is understood to rely heavily on the large-scale deployment of negative emissions technologies (NETs). One option, Bioenergy with Carbon Capture and Storage (BECCS), is prominent in Integrated Assessment Models (IAMs), with projected annual contributions of 8–16.5 Gt_{CO_2} per year of atmospheric carbon dioxide removal whilst contributing 150–300 EJ per year, or 14 to 20% of global primary energy supply, in 2100. Implicit in these scenarios is the assumption that BECCS is a net producer of energy. However, relatively energy intensive biomass supply chains and low power generation efficiency could challenge this ubiquitous assumption. Deploying an energy negative technology at this scale could thus represent a threat to energy security. In this contribution, we evaluate the energy return on investment (EROI) of an archetypal BECCS facility. In order to highlight the importance of biomass sourcing, two feedstock scenarios are considered: use of domestic biomass pellets (UK) and import of biomass pellets from Louisiana, USA. We use the Modelling and Optimisation of Negative Emissions Technologies (MONET) framework to explicitly account for growing, pre-treating, transporting and converting the feedstock in a 500 MW BECCS facility. As an example, we illustrate how the net electricity balance (NE_lB) of a UK-based BECCS facility can be either positive or negative, as a function of supply chain decisions. Power plant efficiency, fuel efficiency for transport, transport distance, moisture content, drying method, as well as yield were identified as key factors that need to be carefully managed to maximise BECCS net electricity balance. A key insight of this contribution is that, given an annual carbon removal target, increasing BECCS' power generation efficiency by using a more advanced biomass conversion and CO_2 capture technology could improve BECCS net electricity balance, but at the cost of increasing the amount of BECCS capacity required to meet this target. BECCS optimal deployment pathway is thus heavily dependent on which service provided by BECCS is most valued: carbon dioxide removal or power generation.

Broader context

It has become apparent from the Integrated Assessment Models (IAMs) mitigation pathways that BECCS is indispensable to achieving climate targets. In most models, BECCS deployment reaches a maximum value of 250 EJ per year by 2100, further deployment being constrained by the limited availability of sustainable biomass assumed in the models. However, this deployment rate relies on the assumption that BECCS is, in all cases, a net energy provider, whereas in reality the converse could be true in the case of an energy intense biomass supply chain and low power generation efficiency. In 2015, bioenergy contributed to 7% of the world primary energy production, with approximately 56 EJ of bioenergy produced. Deploying BECCS at the gigatone scale could therefore increase the current primary bioenergy demand five fold by 2100. In this context, the value of BECCS Electricity Return on Investment (E_lROI) or Net Electricity Balance (NE_lB) could have profound implications for the energy system: an EROI below unity would mean that more energy is used to operate BECCS than what is returned to society, which could compromise energy security, as well as increasing the use of higher EROI technologies, such as fossil fuels, to sustain BECCS in the energy mix. Unintended consequences of this could include an increase in CO_2 emissions, with a potential offset of the carbon dioxide removal service provided by BECCS. Identifying the factors influencing BECCS net electricity balance, and understanding the implications of a negative electricity balance on the world energy demand, is thus crucial when deploying BECCS at the projected scale.

1 Introduction

1.1 BECCS and integrated assessment models

The UNEP Emissions Gap report[1] recently reasserted the importance of negative emissions technologies (NETs) in maintaining a

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"well below 2 °C" temperature trajectory, with contributions as high as 20 Gt_{CO_2} per year by 2100. By combining bioenergy with capture and storage of the CO_2 emitted upon conversion of the biomass, Bioenergy with Carbon Capture and Storage (BECCS) has been identified as a key negative emissions technology.[2–4] Because this technology uniquely removes CO_2 from the atmosphere while providing power, there is a general consensus that BECCS will likely be indispensable to achieving these negative emissions, with projected contributions a high as 8.5 to 16 Gt_{CO_2} per year of carbon removal.[5–7] However, there is an ongoing controversy around BECCS ability to deliver these negative emissions, if at all, in a cost-effective and resource efficient[8–10] way. This has led some to suggest that relying so heavily on greenhouse gas removal (GGR) techniques in general, and BECCS in particular, could represent a moral hazard, preventing us from taking active steps towards climate mitigation today.[11] In addition to contributing to carbon removal, BECCS is also projected to significantly contribute to global energy supply, providing between 100 and 300 EJ per year to the primary energy mix.[6,7] If negative emissions are to be achieved *via* BECCS, in a way that is both sustainable and resource efficient, it is important to understand under which conditions BECCS can be deployed such that it is simultaneously net CO_2 negative, resource efficient, and net energy positive.

1.2 Is BECCS energy positive?

One of the main assumptions underpinning the use of BECCS is most modelling efforts is that BECCS is a net provider of power. However, the energy intensity of biomass supply chains could represent a challenge to this assumption.[10,12] Additionally, the conversion of a lower quality fuel – biomass – combined with CO_2 capture and storage, impose an energy penalty on the system, relative to conventional fossil power generation, resulting in a potentially low power generation efficiency.[13] In their review, Moriarty *et al.*[14] say that there is uncertainty as to the capability of bioenergy to be a net provider of energy, and further argue that were it to pass the "energy test", it might not deliver emissions reduction. Vaughan *et al.*[8] identified seven BECCS assumptions with both high uncertainty and great impact on BECCS performance, and highlighted BECCS total contribution to the energy system as one of them. Smith *et al.*[9] presented a high level analysis showing that BECCS had a positive net energy balance on average, with energy production ranges of 3–40 GJ per $t_{C_{eq}}$ for energy crops. However, the analysis also pointed out the possibility of energy negative scenarios with an energy consumption up to 8.7 GJ per $t_{C_{eq}}$. Nevertheless, BECCS is still consistently represented as a net source of both negative emissions and power in Integrated Assessment Models (IAMs), which explains its prevalence in these models.[7] Understanding the circumstances under which BECCS deployment might lead to a negative energy balance, and the implications for the energy system, is thus crucial to the design of BECCS systems that will make a net positive contribution to climate change mitigation.

1.3 EROI for technology valuation

Energy systems follow the same rule as organic systems: in order to be viable, they need to produce at least as much useful energy as they consume.[15] This is measured by the Energy Return On Investment (EROI), which calculates the ratio of energy output of a system or resource to all the energy inputs required by this system, or to exploit this resource. It is thus a measure of the energy cost of energy: how much energy is required to provide energy in a specific form with a given technology? Deploying a technology with an EROI less than unity, would mean that overall, the technology uses more energy than it returns to society, which would result in the need for this technology to be complemented by other energy sources, preferably with a high EROI, to operate. Hall *et al.*[15] suggest that fossil fuels could typically be used to compensate this energy deficit. From this perspective, if, owing to poor management of the supply chain, BECCS EROI were to be found very low, deploying BECCS at the EJ scale could lead to an increase in fossil fuel use, which could hinder the potential environmental benefits of BECCS deployment, leading to further overshoot of emissions requiring the subsequent additional deployment of NETs, and so on, *ad infinitum*.

Though conceptually simple, there are, however, many caveats associated with the calculation of this metric. The first lies in the definition of the boundaries of the system for which EROI is calculated: what should be considered as the "energy output" of the system, and similarly, what should be considered as "energy inputs".[16] Murphy *et al.*[16] categorised fourteen EROI methodologies, defining three levels of energy output boundaries from extraction (or "mine-mouth") to end-use or point of use, and five levels of energy inputs from direct energy and material inputs to auxiliary services consumption and environmental impacts. As pointed out by the authors, the diversity in methodologies result in a great divergence in EROI values in the literature, with the EROI of modern coal being found between 20 and 67, between 1.6 and 12 for solar collectors power, and 0.8 and 10 for biofuels. Another consequence of this boundary definition is that the criteria of having an EROI above one at extraction or processing might not be enough, as the EROI at the point of use could therefore be lower than one. For example, Hall *et al.*[15] propose that biofuels must provide a minimum EROI of 3 : 1 at processing in order to be a viable alternative to fossil fuels.

Another challenge lies in differentiating energy inputs and outputs in terms of energy quality. Considering that 1 Joule of diesel has the same value as 1 Joule of solar power overlooks the many attributes of an energy source; among service provided, scarcity, exergy, energy density, cleanliness, *etc.*, which overall define its quality.[16] As a first approach, a common but fundamental distinction is made in studies between Primary Energy (PE) sources and Energy Carriers (EC): when calculating EROI based on energy carriers, 1 Joule of electricity is equivalent to 1 Joule of fuel, whereas in a primary energy methodology, all energy carriers vectors are converted back into the primary energy source from which they were generated.[17,18] When the output of the system is electrical energy, considering the electrical equivalent energy of primary energy inputs is another method when performing EROI calculations. In calculating the net electricity balance and the E_1ROI of solar photovoltaic (PV), Dale *et al.*[19] considered the total electrical output, minus, or

divided by, the cumulative primary energy use for the technology supply chain, converted into electrical energy equivalent. Methodologies to convert energy inputs to weight them by quality, price-based adjustment or exergy-based adjustments are further examples which highlight the potential complexity of EROI calculation.[16]

The quality of the energy source is equally important when comparing the EROI of different technologies, and can also be measured by the nature of the service provided by the energy source. Renewables such as wind and solar, which provide ready-to-use electricity, have typically a lower EROI than fossil fuels, which still need to be converted before delivering any form of energy. When comparing energy sources on the basis of similar service provided, the EROI of coal electricity for example, can be found between 12–24,[17] which is of the same magnitude of solar electricity, with values between 6 and 12,[17] and a median at 10.[20]

1.4 The EROI of bioenergy

There are many studies presenting energy analysis or EROI calculations of solid and liquid biofuels, as well as E_1ROI calculations of bioelectricity. Moriarty et al.[14] points out the wide range in these evaluations. The EROI of short rotation willow in Europe has been reported to be in the range 14.4–64.8, and that of Miscanthus in Ireland, between 3.6 and 6.5. In terms of biofuels EROI, US corn ethanol was evaluated at 1.5, Brazilian sugar cane ethanol at 5, corn biodiesel at 1.61, and cellulosic ethanol up to 6. These examples highlight the importance of explicitly considering specific region and feedstock when evaluating the EROI of resources, as biomass yield per hectare for example, may vary strongly from one region to another. Model boundaries also matter in the calculations. Table 1 gathers EROI values adapted from the literature,[10] and highlights the importance of boundary choice when assessing bioenergy energy balance.

From this brief review of the literature, it can be observed that bioenergy EROI has been reported to have a wide range, with values between 2.3 and 84 as a function of biomass type,

origin, and specific supply chain. However, when considering the whole value chain including pre-treatment and transport of the biomass, the range narrows to 3.6 to 15.9 for ready-to-use biomass pellets, and 2.3 and 4.2 for bioelectricity, when including pellet combustion. However, no ranges of EROI values for BECCS are reported in the literature.

The purpose of this study is to deliver an EROI analysis of BECCS, in order to provide insight into the circumstances under which BECCS can be net positive or negative, and to identify the key levers for improving the net energy balance. The remainder of the paper is structured as follows. Section 2 presents the model and assumptions used for this analysis, and Section 3 the details of the supply chain scenarios considered for this study. Section 4 presents the cumulative energy demand, cumulative EROI and cumulative net electricity balance of a UK-based BECCS facility using domestic or imported biomass pellets. In Section 5, an energy flow analysis provides insights as to the key levers of BECCS electricity balance improvement, including BECCS power generation efficiency. In meeting its long-term climate change commitments, the UK has set the target of achieving a net zero CO_2 economy by 2050. As the UK economy is not anticipated to be carbon neutral by 2050, meeting this target will rely on the net removal of CO_2 from the atmosphere, via the deployment of negative emissions technologies at the rate of 50 Mt_{CO_2} per year.[33] The impact of BECCS power generation efficiency on the net electricity balance, the BECCS capacity and amount of resources – land and water – required to remove these 50 Mt_{CO_2} per year with UK-base BECCS fleets is also evaluated in Section 5. Finally Section 6 discusses the results and their socio-economic implications.

2 Methodology

This study uses the Modelling and Optimisation of Negative Emissions Technologies (MONET) framework, presented previously.[10] This model enables the calculation of the energy, water, carbon and land intensities of growing, harvesting, processing, transporting biomass feedstock to the UK, and converting in a 500 MW

Table 1 EROI values in the literature. Variations are observed depending on region of production, biomass type and supply chain boundaries

Crop, region	EROI[a]	Boundaries
Miscanthus, average[21]	34.6	Raw biomass: production only no irrigation
Miscanthus, Poland[22]	23.4	Raw biomass: production only no irrigation, 4k transport
Miscanthus, Germany[23]	14.4	Bioelectricity: production (bale), 100k transport, chopping and milling for combustion
Miscanthus, Ireland[24]	3.6	Pellet: production (bale) no irrigation, 100k transport, drying and pelleting
Switchgrass, USA[25]	9.5–12	Raw biomass: production (bale or chopped) incl. irrigation
Switchgrass, USA[26]	74–84	Raw biomass: production (bale) no irrigation, storage
Switchgrass, USA[21]	16.4	Raw biomass: production only no irrigation
Switchgrass, USA[27]	11–20	Raw biomass: production only no irrigation (bale, chopped), transport 40k
Willow, Sweden[28]	20.9	Raw biomass: production and 50k transport
Willow, average[21]	12	Raw biomass: production only no irrigation
Willow, Belgium[29]	11–54	Raw biomass: production only no irrigation
Wood pellets, Australia and Russia[30]	2.4–15.9	Pellet: production, drying (50% of the feedstock), pelleting and transport
Willow, Poland[22]	15.5	Raw biomass: production only no irrigation, 4k transport
Wheat straw, New Zealand[31]	4.2	Bioelectricity: collection (bale), 90k transport, grinding, combustion
Wheat straw, UK[32]	2.3	Bioelectricity: collection (bale), 40k transport, conditioning, combustion

[a] EROI of biomass pellet or E_1ROI of bioelectricity.

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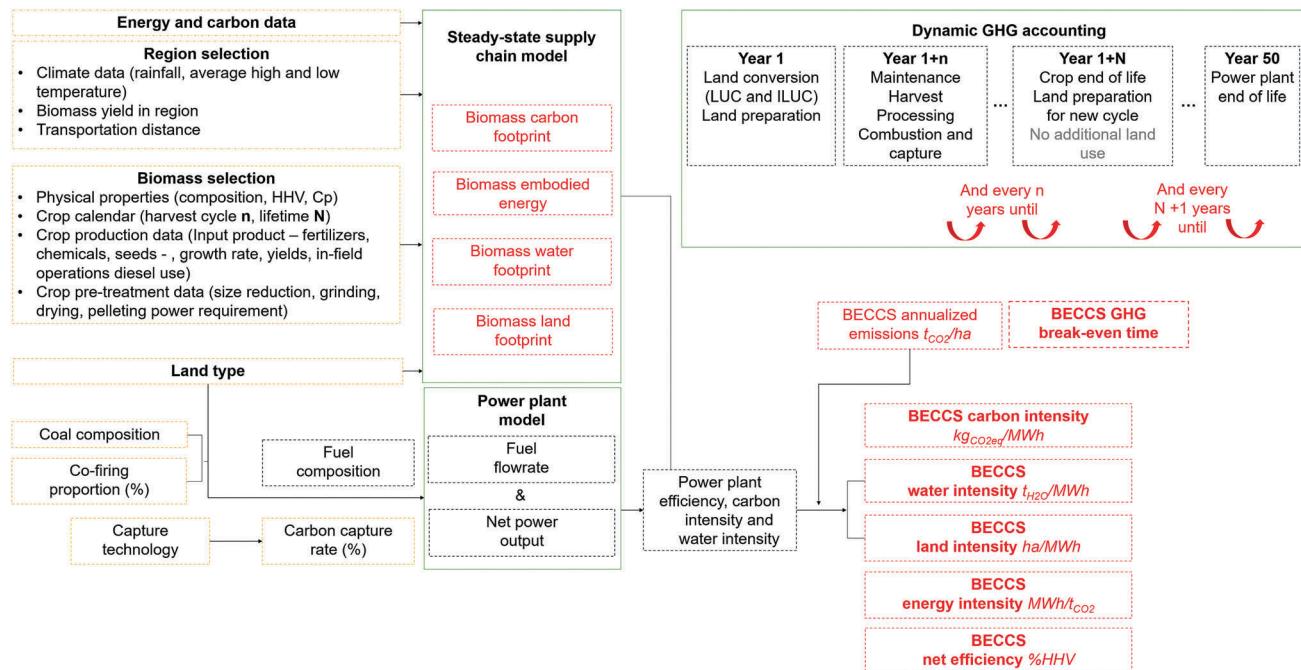
Fig. 1 Overview of the MONET model as presented in Fajardy and Mac Dowell.[10] The model takes energy, carbon, region, biomass and land data as inputs, and computes the carbon intensity, water intensity, land intensity and net efficiency of a UK-based BECCS system operating with a given biomass type, imported from a given region of the world, and grown on a given land type. The carbon balance was also implemented dynamically to calculate the system carbon breakeven time and annualised carbon removal.

thermal power plant combined with post-combustion capture technology. We consider four distinct biomass feedstock: miscanthus and switchgrass for perennial grasses, short rotation coppice willow for dedicated woody biomass crop, and wheat straw for agricultural residues. Five different regions of the world are considered as regions of import for the UK: Brazil, Europe, China, India, and the USA. Fig. 1 presents an overview of the model.

2.1 Energy modelling and extensions

2.1.1 Spatial granularity. For our current study, the spatial granularity of MONET was increased from the macro-region level to the sub-region level – Brazil states, Chinese provinces, European states, *etc.*, reaching a total of 170 sub-regions sr. Rather than averaging the model input data – for example crop yield, weather data or electricity carbon footprint, the model input data was desegregated at the sub-region level. A consequence of this discretisation in a change in the computation of the road distance for biomass pellet transport. Sub-regions are polygons represented geographically by the latitude $Y_C(sr)$ and longitude $X_C(sr)$ of their centroid. Similarly, ports are represented by their latitude $Y_P(p)$ and longitude $X_P(p)$. The road distance considered in the model is the euclidian distance between this points, corrected by a region tortuosity factor $t(sr)$:

$$D_{road}(sr,p) = t(sr) \times R_{earth} \times arcos(\sin Y_P(p)) \times \sin Y_C(sr)$$
$$+ \cos Y_P(p) \times \cos Y_C(sr) \times \cos(X_C(sr) - Y_P(p)) \quad (1)$$

Approximate tortuosity factors were computed for each sub-region sr, by dividing the road distance of the centroid to the

nearest port, by the euclidian distance between these two points.

2.1.2 Energy modelling. Prior to being combusted, biomass needs to be cultivated, harvested, ground, pelleted, transported, and further milled at the power plant. These elements of the value chain require many energy inputs in the form of diesel, natural gas, electricity, fuel, or chemicals. In a previous contribution,[10] the embodied energy (EE) and BECCS net chain efficiency was calculated. Building upon various EROI methodologies developed by Hall *et al.*,[15,20] Murphy *et al.*,[16] Raugei *et al.*[17] and Dale *et al.*,[19] we extended MONET by performing a dynamic accounting of the system energy inputs and outputs over time. This extension enabled the calculation of the following indicators:

– Energy carrier demand $E_cD(sr,b,yr)$, the sum of all specific annual energy inputs $EI_cD(sr,b,yr,k)$ in the forms of energy carrier k (electricity, diesel, natural gas, fuel) required along the BECCS value chain, at year yr, per biomass type b, imported from sub-region sr. The cumulative energy carrier demand $CE_cD(sr,b,yr)$ is then calculated as the summation of all inputs from year 1 to a given year, yr. It can be expressed per hectare of land or per ton of biomass pellet delivered at the power plant:

$$CE_cD(sr, b, yr) = \sum_1^{yr} \sum_k EI_cD(sr, b, yr, k) \quad (2)$$

– Cumulative primary energy demand $CE_pD(sr,b,yr)$, the cumulative sum of all energy inputs $EI_pD(sr,b,yr,k)$ in the forms of primary energy required along BECCS value chain at a given yr through a BECCS project. This metric is calculated by converting the $EI_cD(sr,b,yr,k)$ into primary energy equivalent,

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using an energy carrier to primary energy conversion factor ECToPE(k) of each energy carrier k:

$$CE_pD(sr, b, yr) = \sum_{1}^{yr} \sum_{k} EI_pD(sr, b, yr, k) \quad (3)$$

$$EI_pD(sr,b,yr,k) = EI_cD(sr,b,yr,k) \times ECToPE(k) \quad (4)$$

where $k \in \{$diesel, heavy fuel oil, natural gas, electricity$\}$.

For fuels, *i.e.* diesel, heavy fuel oil, natural gas, ECToPE(k) can be calculated from:

$$ECToPE(k) = 1 + \frac{1}{EROI(k)} \quad (5)$$

where EROI(k) is the EROI of fuel k. For electricity however, the $EI_pD(sr,b,yr,electricity)$ is converted back into primary energy by using the region average power generation efficiency $\eta_{grid}(sr)$:[34,35]

$$ECToPE(sr, electricity) = \frac{1}{\eta_{grid}(sr)} \quad (6)$$

– Cumulative electricity demand $CE_lD(sr,b,yr)$, the sum of all primary energy inputs converted into electrical energy equivalent:

$$CE_lD(sr, yr) = \sum_{1}^{yr} \sum_{k} EI_pD(sr, b, yr, k) \times PEToEl(sr, k) \quad (7)$$

where $k \in \{$diesel, heavy fuel oil, natural gas, electricity$\}$.

For fuels, *i.e.* diesel, heavy fuel oil, natural gas, ECToPE(k) is to conversion efficiency of the fuel k to electricity:

$$PEToEl(sr,k) = \eta_{fuel}(sr,k) \quad (8)$$

For electricity, $EI_lD(sr,b,yr,electricity)$ is simply equal to $EI_cD(sr,b,yr,electricity)$:

$$EI_lD(sr,b,yr,electricity) = EI_cD(sr,b,yr,electricity) \quad (9)$$

– Cumulative primary energy generated, $CE_pG(sr,b,yr)$, the cumulative bioenergy in the form of biomass pellets delivered to the power plant at year yr. This metric can be expressed per hectare of land:

$$CE_pG(sr,b,yr) = HHV(b) \times CBio(sr,b,yr) \quad (10)$$

where $CBio(sr,b,yr)$ is the cumulative amount of biomass pellets delivered at the BECCS facility at year yr. $CE_pG(sr,b,yr)$ can also be expressed per ton of biomass pellet, in which case we have:

$$CE_pG(sr,b,yr) = HHV(b) \quad (11)$$

– Cumulative electricity generated $CE_lG(b)(sr,b,yr)$, the cumulative bioelectricity delivered by a BECCS facility at year yr. This metric can be expressed per hectare of land or per ton of biomass pellet, and is related to the $CE_pG(sr,b,yr)$ by the power generation efficiency of the BECCS plant:

$$CE_lG(sr,b,yr) = CE_pG(sr,b,yr) \times \eta_{plant}(b) \quad (12)$$
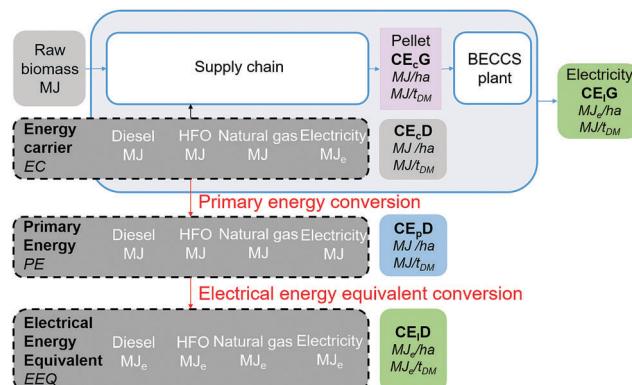
Fig. 2 Overview of the BECCS dynamic energy model. Net electricity balance, electricity return on investment and electricity pay-back time are calculated based on these metrics.

– Energy return on investment EROI(sr,b,yr), the ratio of the cumulative primary energy generated to the cumulative primary energy demand:

$$EROI(sr, b, yr) = \frac{CE_pG(sr, b, yr)}{CE_pD(sr, b, yr)} \quad (13)$$

– Electricity return on investment $E_lROI(sr,b,yr)$, the ratio of the cumulative electricity generated to the cumulative electrical energy equivalent demand:

$$E_lROI(sr, b, yr) = \frac{CE_lG(b)}{CE_lD(sr, b, yr)} \quad (14)$$

– Net electricity balance $NE_lB(sr,b,yr)$, the difference between the electricity generated by the system and the cumulative electricity demand along BECCS value chain:

$$NE_lB(sr,b,yr) = CE_lG(sr,b,yr) - CE_lD(sr,b,yr) \quad (15)$$

– Electricity pay-back time $E_lPBT(sr,b)$, the time required for the E_lROI to be above one:

$$E_lPBT(sr, b) = \sum_{yr} \{yr|E_lROI(sr, b, yr) < 1\} \quad (16)$$

Similarly, another definition is the time required for the net electricity balance to be positive:

$$E_lPBT(sr, b) = \sum_{yr} \{yr|NE_lB(sr, b, yr) < 0\} \quad (17)$$

Fig. 2 provides an overview of the BECCS energy model and its key indicators.

In the case of chemical inputs (fertilizers, lime, herbicide and pesticide), MONET explicitly considers them by including the manufacturing energy of these inputs. As these chemicals are usually made from natural gas, this embodied energy is considered both as an energy carrier and primary energy input.[18]

3 Thought experiment

A UK-based 500 MW dedicated biomass pulverized fuel power plant, combined with amine-based post-combustion capture
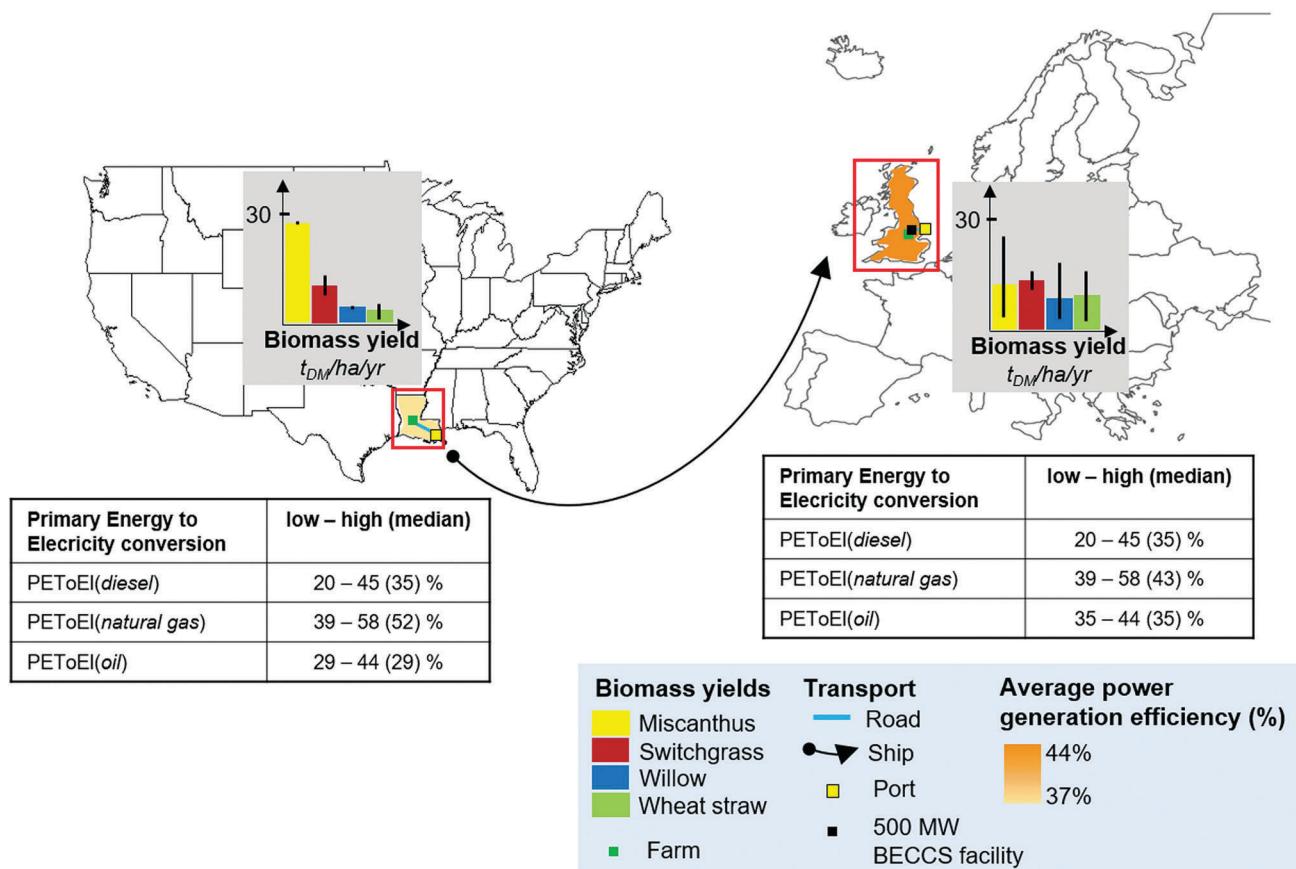
Fig. 3 Case studies and input data considered in the model. Biomass yield (bar chart), primary energy to electricity conversion coefficients for each fuel (table), and average efficiency of the region power generation (region colouring) are given for each region in the low, median and high scenario. Biomass yield is on average higher in the oversea scenario, while the average efficiency of power generation is lower, which has a direct impact on the power to primary energy conversion when computing the EROI of the overall system. Higher yield variability in the UK is due to a higher availability of yield values in the literature for the UK than for Louisiana.

technology was considered as the main BECCS pathway for the UK in this analysis. Two archetypal feedstock supply chains were considered: domestic pellets and imported pellets from overseas. The purpose of these two scenarios is to compare the energy and carbon intensities of using local biomass, hence minimising transport, with importing biomass from a potentially more productive region, close to the coast, which requires oversea shipping. The region of import selected for the purpose of this study was Louisiana, as this is where the pelleting plants and port terminal owned by the UK DRAX power plant, which sources over 50% of its pellet supply from the USA, are located.[36] Fig. 3 gives a graphical representation of these two thought experiments, including key regional input data such as biomass yield, grid power generation efficiency, and primary energy to electrical energy conversion coefficients for the different fuels involved in BECCS value chain. As observed in Fig. 3, biomass yield is on average higher in the oversea scenario, while the average efficiency of power generation is lower, which has a direct impact on the power to primary energy conversion when computing the EROI of the overall system. Both options were evaluated with the low, median and high values of the input parameters, resulting in a low, median and high scenarios for the results. It is worth noting that as more data

was available for the UK than for Louisiana, the uncertainty ranges were usually larger for the UK.

Table 2 in Appendix A summarises the low, median and high values of some of the key model input data in both pellet supply chain scenarios, with their references.

4 BECCS net electricity balance

4.1 Cumulative energy demand of BECCS

The cumulative energy demand of BECCS was calculated in terms of energy carrier, primary energy and electrical energy equivalent, over the lifetime of a BECCS project which was considered to be fifty years, expressed in GJ per ha, or in GJ per t_{DM}. When expressed in GJ per t_{DM}, the cumulative energy demand is the same as the embodied energy (EE) of the dried pellet delivered at the power plant. These results are presented in Fig. 9 in Appendix B. It was observed that the cumulative energy demand is strongly dependent on the region of origin and biomass type. As expected, the cumulative energy demand expressed in terms of primary energy presents the numerically largest result, between 1.8 and 17.2 GJ per t_{DM}, with large contributions from the electricity inputs such as grinding, pelleting and pellet

grinding. The cumulative energy demand in energy carrier results in a numerically smaller value, between 1.2 and 14.1 GJ per t_{DM}, with larger contributions from fossil fuel inputs such as farming, transport and drying. Finally, the energy demand in electrical energy equivalent is the lowest, with values between 0.7 and 7.9 GJ per t_{DM}. EROI methodology therefore impacts the total cumulative energy demand, as well as the main drivers of this energy demand. One must therefore be cautious when choosing one methodology over the other when identifying the key levers of improvement of BECCS net energy balance. Wheat straw has the lowest cumulative energy demand. This can be explained by the fact that, in MONET, wheat straw is considered to be an agricultural residue, and all the energy inputs – fertilizer and in-field operations – associated with the production of wheat grain, are not allocated to the straw. However, straw collecting and additional fertilizer application due to removal of the straw from the field were accounted for. Naturally, importing pellets from Louisiana as compared to using domestic pellet from the UK increases the transport contribution. However, as can be seen in the case of miscanthus, the transport energy contribution increase can be almost compensated by the decrease of other contributions such as chemicals, and in field operations, due to a higher crop yield.

4.2 E_lROI and net electricity balance

Having first calculated pellets' cumulative energy demand and BECCS cumulative electricity produced over the project lifetime, we calculated BECCS EROI and E_lROI as a function of time. Fig. 4 presents the evolution of the values of biomass pellets EROI (a) and BECCS E_lROI (b) over time.

Two specific insights can be obtained from Fig. 4: the median cumulative EROI and E_lROI values over the project lifetime, as well as the electricity pay-back time. It is observed that for electricity positive systems, the E_lPBT varies from 1 to 4 years. In the case of willow, upon importing pellets as opposed to using domestic pellets, the system becomes energy negative, as the lifetime E_lROI is found to be below one. The range of values obtained for the lifetime cumulative EROI and E_lROI are presented in Fig. 5.

As observed in Fig. 5, the median lifetime cumulative EROI varies from 1.1 to 10.3. These values are consistent with the biomass pellet EROI range of 3.6 to 15.9 reported in the literature, considering the variability in the input data and EROI calculation boundaries. In terms of lifetime cumulative E_lROI, values drop to 0.5 for willow from Louisiana, with maximal E_lROI attained for domestic switchgrass at 5.7.

Another way to look at the dynamic energy return is to analyse the net electricity balance of the system, over the course of a project lifetime. These results are presented in Fig. 6.

As presented in Fig. 6, depending on the region and feedstock scenario, but also on the model input data (yield, moisture content, chemical application rate, fuel efficiencies, embodied energy in fuel and chemicals, primary energy to electrical equivalent conversion coefficients, power generation efficiency, *etc.*), BECCS can lead to both negative and positive energy balances.

Overall, using agricultural residues such as wheat straw could be a promising option, as operating BECCS with this feedstock overall leads to a positive energy balance. However, this statement requires several caveats. First, the lifetime cumulative energy generation per
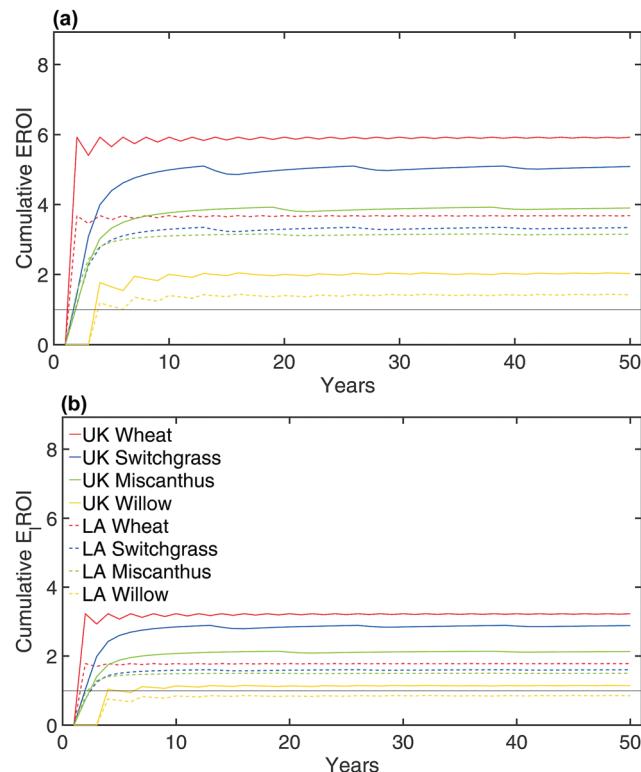
Fig. 4 Dynamic EROI of biomass pellets (top) and dynamic E_lROI of abated bioelectricity (bottom) for the two feedstock case studies, in the median scenario. In the case of willow, upon importing pellets as opposed to using domestic pellet, the system becomes energy negative, as the lifetime E_lROI is found below one. For energy positive systems, the E_lPBT varies from 1 to 4 years.
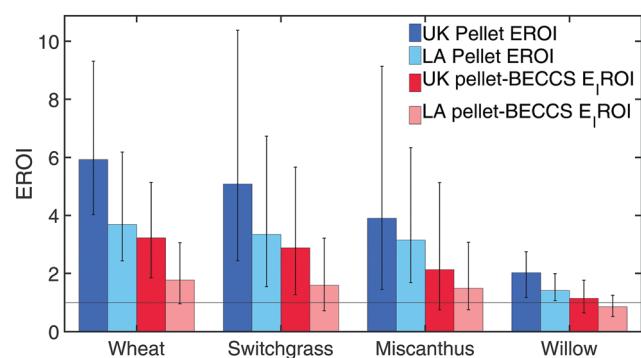

Fig. 5 Lifetime EROI of biomass pellets (blue) and lifetime E_lROI of abated bioelectricity (red) for the two case studies. The lifetime cumulative EROI vary from 1.1 to 10.4, whereas the lifetime cumulative E_lROI values drop to between 0.5 to 5.7.

hectare of such a system is low owing to a low straw yield per hectare, resulting in an inefficient use of the land for energy production *via* BECCS. Moreover, considering straw as a waste from grain production stands a long as wheat grain is not grown as an energy crop, which could be challenged if all wheat straw production was used for BECCS. Finally, BECCS deployment through agricultural residues will also be limited by regional wheat availability. Using energy dedicated crops could be more challenging because of
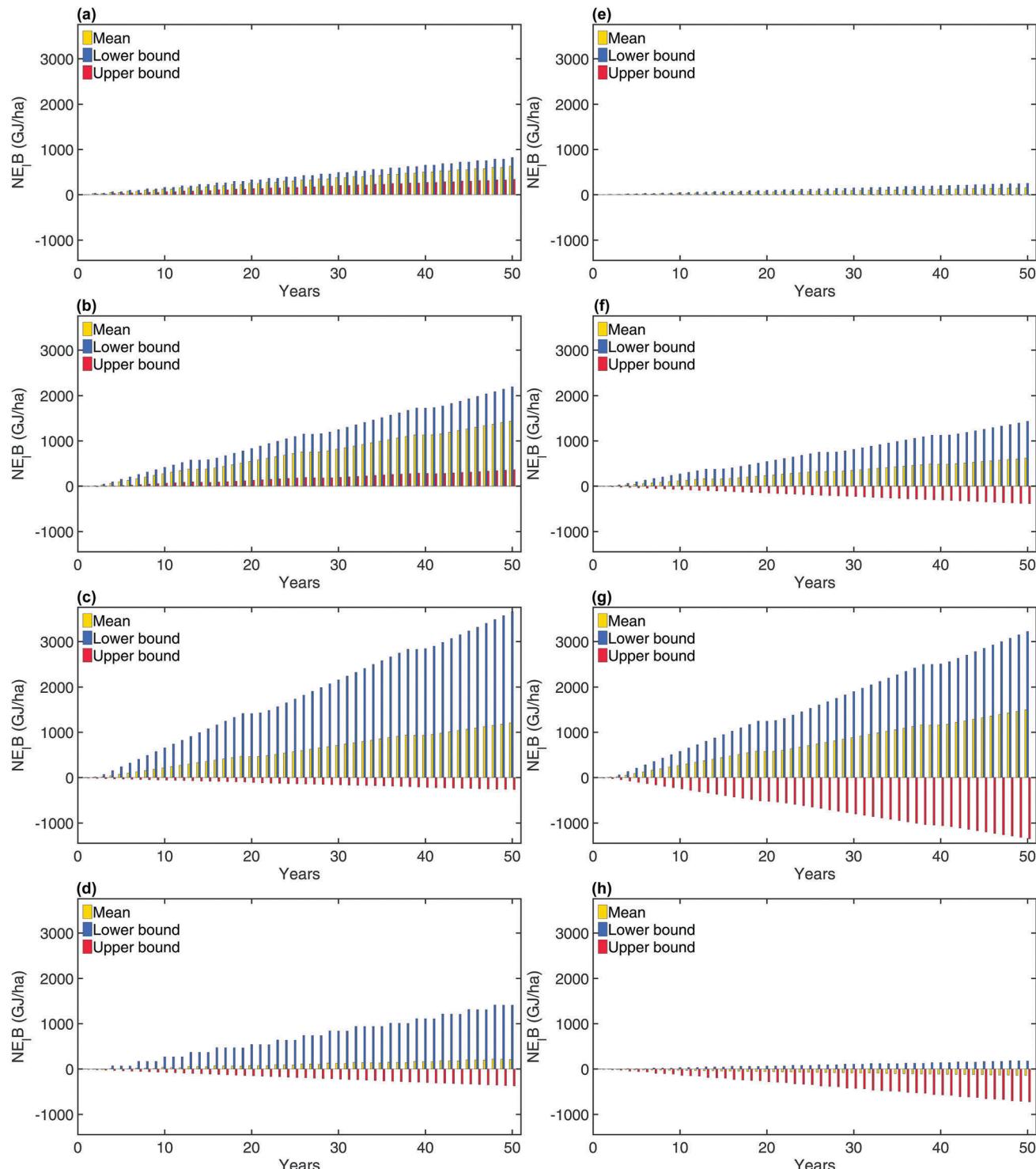
Fig. 6 Cumulative net electricity balance of a BECCS facility using wheat straw (a and e), switchgrass (b and f), miscanthus (c and g), and willow (d and h) sourced from the UK (left) and Louisianna (right), in the high, mean and low scenarios. Depending on the scenario and case study, BECCS can lead to both positive and negative energy balances.

yield variability, as well as higher cumulative energy demand. In the case of willow, a lower yield, longer harvest cycle and higher cumulative energy demand result in a very low cumulative net power production in the mean and high scenarios, with an net energy negative balance in the mean scenario in the case

of pellet imports from Louisiana. However, using higher productive grasses such as Miscanthus and Switchgrass could result in high cumulative net energy balance over fifty years, with values as high as 3500 GJ per ha of net electricity produced in the case of Miscanthus from the UK.

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5 Improving BECCS net electricity balance

5.1 Identification of main energy losses

A energy flow analysis was performed on the system to identify the main energy losses along BECCS value chain, and their impact on BECCS electricity balance. Fig. 7 presents the energy flow diagram of BECCS systems operating on domestic and imported biomass feedstock.

Biomass conversion and CCS in the BECCS facility, followed by road transport, drying, and farming (including inputs) constitute the main energy losses along the chain. Power generation efficiency, transport fuel efficiency, moisture content and yield are therefore key parameters to be optimised when maximising BECCS net electricity balance. In terms of management of these levers, yield, moisture, and transport fuel efficiency are highly dependent on the feedstock and region of import, and can therefore be complex to predict and control. Power generation efficiency, however, as purely linked to the technology of the UK-based facility, constitutes a more tractable level to improve BECCS net electricity balance. In this analysis, the power plant power generation efficiency is calculated in the model based on the fuel quality (HHV, composition, moisture content) and CO_2 capture rate, for a state-of-the-art amine based post-combustion capture technology, with a solvent regeneration heat duty of approximately 3.6 GJ per t_{CO_2}. With biomass pellets at 5% moisture and a power plant operating at 100% co-firing and 90% capture rate, the efficiency is found to be around 26%$_{HHV}$ for all scenarios. As shown by Bui et al.,[13] BECCS efficiency can be increased by using advanced solvents with reduced heat duty, as well as by implementing heat integration options such as heat recovery from the exhaust gas to provide the solvent regeneration heat duty. With such modifications, it was found that BECCS power generation efficiency could be increased to 38%$_{HHV}$. This option was subsequently evaluated in MONET.

5.2 Power generation efficiency improvement and implications for resource mobilisation

In this section of the analysis, we calculate the annual net electricity production of a UK BECCS fleet operating to remove 50 Mt_{CO_2} per year. Using MONET, this target scenario also enables the calculation of the annual land, water and BECCS capacity requirements to meet this carbon removal target.

Fig. 8 represents the net energy balance, land use, water use, BECCS capacity and amount of CO_2 removed per unit per year for 26% and 38% efficient BECCS fleets, for all pellet supply scenarios. It is worth noting that the amount of CO_2 removed per unit per year, and BECCS deployed capacity, are inversely proportional.

As can be observed from Fig. 8, BECCS capacity requirement and resource mobilisation in order to meet a given carbon removal target is entirely case specific. Meeting the UK's 2050 target will require between 8–14 GW of installed capacity, which represents 14 to 25% of the UK annual electricity generation by 2050.[37] In terms of resources, between 2–175 Bm^3 per year of water and between 232 ha and 22 Mha of land would be required, domestic wheat straw being the best case scenario,

and imported willow pellets, the worse. It is important to note that these scenarios were considered to compare two archetypal supply chains, and no constraint on regional land and water availability were considered in their implementation. As a reality check, in the BECCS via domestic wheat straw scenario, 47 Mt of wheat straw, hence about 36 Mt of wheat grain, would be required per year, which is more than double the UK annual wheat production in 2014.[38] A combination of wheat straw and energy dedicated crops would therefore be required to meet the UK carbon removal target via BECCS with domestic biomass. Similarly, relying on imported willow pellets to meet the UK carbon removal target would lead to the mobilisation of 22 Mha of land in Louisiana. In this study, we assume that energy dedicated crops are grown on marginal land to avoid direct and indirect land use change.[10] As the total area of Louisiana is approximately 13.5 Mha, there would not be enough land, let alone marginal land, to meet the UK removal target via this option. Designing optimal BECCS supply chains to meet a given carbon removal target will therefore need to consider a combination of regions, and specifically account for regional land and residue availability. It is also worth noting that wheat straw very low land use and water use is also due to the fact that straw was considered as a waste from wheat grain production, therefore not accounting for land and water use for wheat farming in wheat straw CO_2, water and land balance. This assumption could be challenged if wheat straw use for BECCS started to impact wheat production for food. In terms of net electricity generated, this BECCS fleet can generate up to 137 PJ per year in the case of domestic wheat straw, but also require up to 66 PJ per year in the case of willow pellets imported from Louisiana. To put these values in context, in 2014, electricity generation from bioenergy in the UK amounted to approximately 118 PJ.[39] Meeting the UK annual carbon removal target per year could thus potentially result in a 16% increase of bioelectricity supply when using domestic agricultural residues such as wheat straw, but could also consume the equivalent of 50% of the current UK bioelectricity supply when operating on willow pellets imported from southern USA. This could have profound implications as to UK electricity system design, with current forecast relying on BECCS as a net source of electricity, rather than as a net sink of electricity. Increasing BECCS power generation efficiency would improve the system net energy balance, but would also result in a lower CO_2 removal per BECCS unit, hence requiring greater BECCS facility, as we have discussed previously,[40] and to a smaller extent, a higher amount of land and water required to meet a given carbon removal target.

6 Discussion

In this analysis, we found that BECCS E$_1$ROI is highly variable depending on the feedstock and region of import scenarios considered, with values be as low as 0.5 and as high as 5.7. While lower bounds values are therefore energy negative (EROI below unity), upper bounds values were found in the range of solar PV. They remain however lower than the E$_1$ROI of

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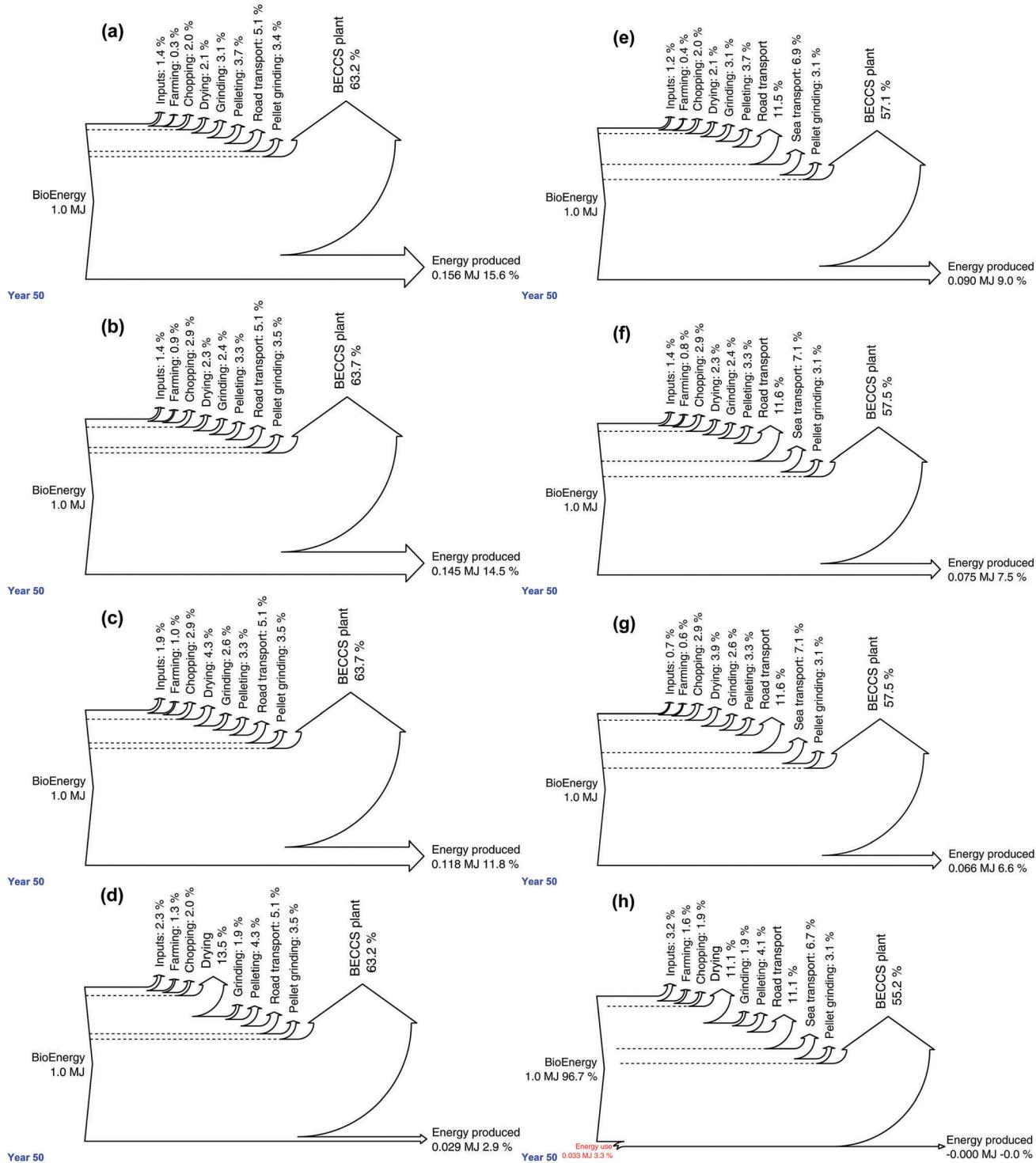
Fig. 7 Energy flow diagram of BECCS value chain for domestic (left) and imported (right) wheat straw (a and e), switchgrass (b and f), miscanthus (c and g), and willow (d and h) pellets. Biomass conversion and CCS in the BECCS facility, followed by road transport, drying, and farming constitute the main energy losses along the chain. Power generation efficiency, transport fuel efficiency, moisture content and yield are therefore key levels to be optimized. In the case of miscanthus, an increase in transport energy losses for imported pellets, can almost be compensated by a decrease of farming losses because of an increased yield.

coal fired electricity, which was evaluated in the 12–24 range in Raugei *et al.*[17] However, adding CCS to coal electricity could substantially lower the E$_I$ROI of coal electricity.[20] This would mean that, in some scenarios, BECCS would be competitive

with other low-carbon energy technologies, whilst also providing the additional service of atmospheric carbon dioxide removal. Though careful management of BECCS value chain can potentially lead to competitive E$_I$ROI values, scenarios

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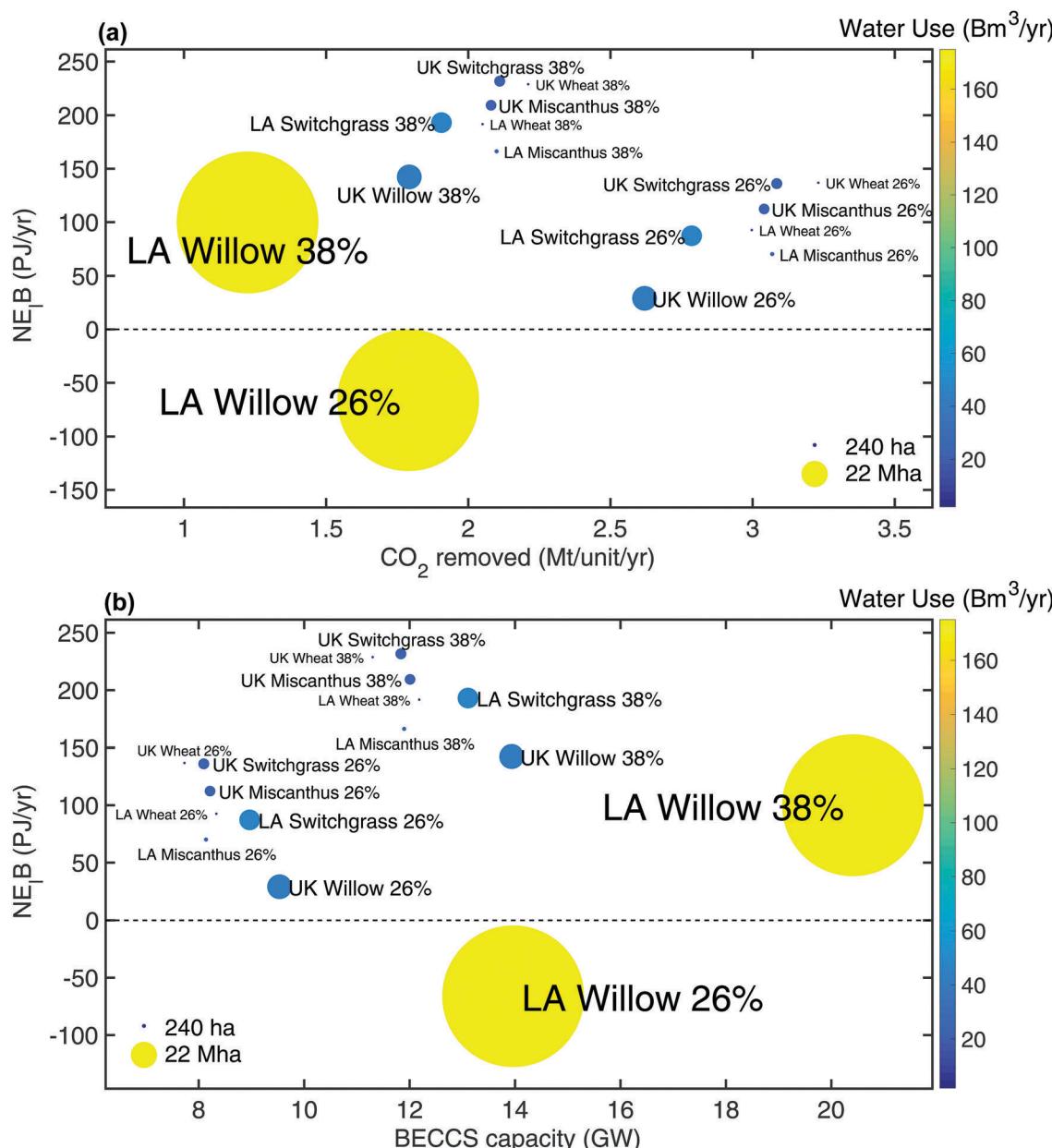
Fig. 8 Mean net electricity balance (y-axis), water use (color scale), land use (marker size) as a function of CO_2 removed per unit per year (top) and capacity requirement (bottom), for a 26% and 38% efficient BECCS fleet. BECCS deployed capacity can be as high as 14 GW and as low as 8 GW, with annual water use between 2 and 175 Bm^3 per year, and the land use between 232 ha and 22 Mha. The deployed BECCS fleet can generate up to 137 PJ per year, but also require up to 66 PJ per year in the case of willow pellets from Louisiana. Increasing BECCS power generation efficiency would improve the system net energy balance, but would also result in a lower CO_2 removal per BECCS unit, hence in a higher BECCS capacity, and to a smaller extent a higher amount of land and water required to meet a given carbon removal target.

with low E_lROI could also be a reality. This would have several socio-economic implications. As observed by Hall $et\ al.$,[15] biofuels with EROI values below $3:1$ might need to be subsidised by fossil fuels, in the sense that their deployment would rely on the energy viability of fossil fuels, in order to provide value to the energy system. This would mean that BECCS scenarios for which more energy is consumed than electricity is produced, could lead to an increase in fossil fuel use. This could threaten world energy security, as well as BECCS' carbon removal potential, as an increase in fossil fuel CO_2 emissions could

offset the negative emissions provided by BECCS. However, the implication may be nuanced when considering BECCS might not be solely deployed in the purpose of generating power, but also, and primarily, to remove CO_2 from the atmosphere. In a previous contribution,[40] it is shown that, providing a negative emissions credit is available to the operator of the BECCS facility, it is more profitable for a BECCS power plant to operate on a base-load fashion, therefore removing CO_2 constantly, and dispatching power on the electricity grid on a load following basis. This underlines that BECCS' service of CO_2 removal,

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could be more important than energy generation. It is also important to highlight that there are important trade-offs between carbon removal and power generation. As noted by Mac Dowell and Fajardy[40] and Bui et al.[13] less efficient power plant remove more CO_2 per year or per MW h_e generated than their more efficient counterparts. This was also observed in this analysis, as increasing BECCS efficiency improved BECCS net electricity balance and E_lROI, hence its value to the energy system, but also resulted in a decrease in the amount of CO_2 removed per facility per year, hence in a larger BECCS fleet required to meet an annual carbon removal target. To a smaller extent, resource mobilisation – land and water – also increased. Consequently, from an investment perspective, and depending on the source of the investment – negative emissions or energy sector – BECCS E_lROI might be less important than for other power generation technologies. To put BECCS net electricity balance in perspective, Direct Air Capture (DAC), another option for carbon dioxide removal, could require between 335 and 1135 PJ per year to remove 50 Mt_{CO_2} per year,[41–43] which is still 5 to 17 times higher than BECCS energy requirement when deployed with willow from Louisiana.

7 Conclusion

We found that BECCS dynamic E_lROI profile is strongly case specific. Depending on the scenario, we found that lifetime E_lROI values could be found within the range of 0.5–5.7. This means that BECCS electricity could be equally to "negative value" to the energy system – negative energy balance – as well as competitive with PV and decarbonised thermal power plants (coal or gas with carbon capture and storage). Large-scale deployment of low E_lROI scenarios without due consideration of this nuance could represent a risk to both energy security and carbon dioxide removal, with a potential increase of fossil fuel use, and subsequent CO_2 emissions, to compensate for BECCS net electricity negativity. Given that we have shown that BECCS can be both carbon positive and negative and both energy positive and negative, the scope for unintended consequences is vast.

This contribution also highlighted the main energy losses along BECCS value chain: biomass conversion and CCS, followed by transport (road), drying, and farming (including inputs) represented over 80% of the energy losses for high moisture and low yield biomass such as willow pellets. Power plant efficiency, fuel efficiency for transport, transport distance, moisture content, drying method, as well as yield were thus identified as key parameters that need to be carefully controlled to maximise BECCS net electricity balance. There are also important trade-offs between these levers. In most cases, a greater travel distance from a region naturally resulted in a higher cumulative energy demand of the value chain, therefore decreasing the EROI and E_lROI. However, it was found that greater travel distances could almost be compensated for by a reduction in energy requirement for farming, when importing biomass from a region with superior yield. In summary, given the manifold contributions which determine the net energy balance of BECCS, it is important to resist the temptation to draw broad, general conclusions from a potentially narrow range of specific case studies.

Finally, we found that improving BECCS power generation efficiency could drastically reduce BECCS energy losses, but would also increase the amount of BECCS installed capacity required to meet an annual carbon removal target, and thus the financial cost associated with meeting that target. There is therefore a clear trade-off between BECCS annual carbon removal potential and power generation, and consequently between BECCS annual carbon removal potential and E_lROI. As BECCS uniquely has the potential to provide both carbon removal and electricity, a lower E_lROI could thus be compensated by a higher annual carbon removal, and vice versa. BECCS value to the system, as well as optimal deployment pathway, will therefore strongly depend on the nature of the service for which BECCS is primarily deployed, carbon removal or power generation.

Conflicts of interest

There are no conflicts to declare.

Appendices

A. Energy model input data

Table 2 Energy model key input data[a]

Parameter	Unit	Domestic biomass	Imported biomass	Ref.
Willow yield	t_{DM} per ha per year	4–17 (9)	5.1	10
Switchgrass yield	t_{DM} per ha per year	11–15 (13)	7.4–12.6 (10.8)	10
Miscanthus yield	t_{DM} per ha per year	5–24.1 (12.8)	28.1	10
Wheat straw yield	t_{DM} per ha per year	4.3–15.7 (9.4)	1.9–6.4 (4.1)	10
Electricity carbon footprint	kg_{CO_2} per MJ	135–162 (149)	149	10, 44 and 45
η_{grid}	%	44	37	35
ECToPE(electricity)	MJ per MJ	2.27	2.70	Own calculation
PEToEl(diesel)	%	20–45 (35)	20–45 (35)	35
PEToEl(natural gas)	%	39–58 (52)	39–58 (43)	34 and 35
PEToEl(fuel oil)	%	29–44 (29)	35–44 (35)	34 and 35
Road distance (truck)	km	50	300	Own calculation
Ship distance (ship)	km	0	9045	Own calculation
Road tortuosity	—	1.4	1.1	Own calculation

[a] For complete model data and references, refer to Fajardy and Mac Dowell, 2017.[10]

B. Cumulative energy demand
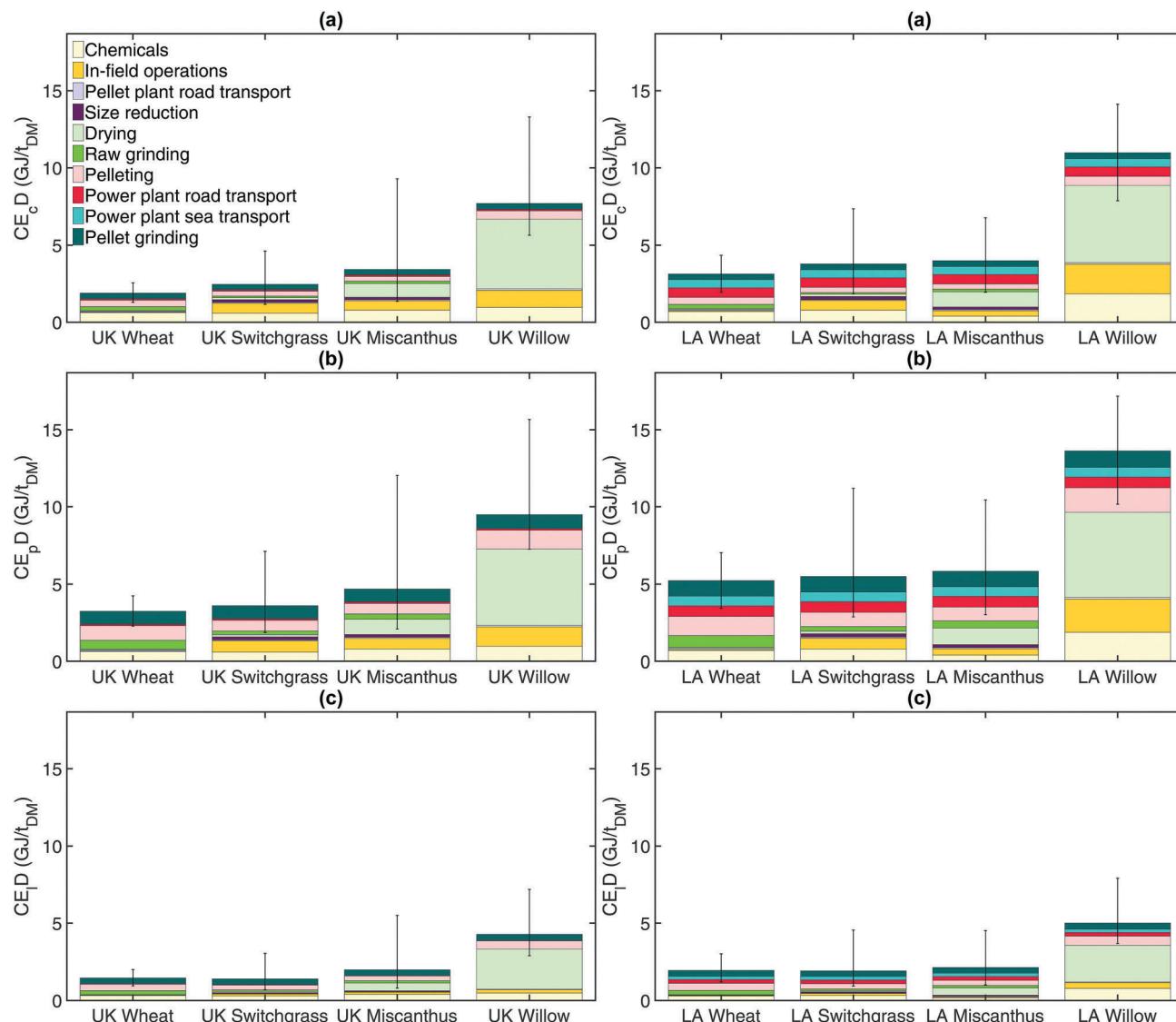
Fig. 9 Cumulative energy demand of domestic (left) and imported (right) biomass pellets for different system boundaries: energy carrier (a), primary energy (b) and electrical energy equivalent (c). Cumulative energy demand is strongly dependant on the region, biomass and methodology chosen. Importing biomass pellet does not necessarily increase the energy demand as opposed to using domestic biomass. In the case of miscanthus, the transport energy contribution increase is almost compensated by the decrease of other contributions (chemicals, in field operations), due to a higher crop yield.

Acknowledgements

References

1 UNEP, *The Emissions Gap Report*, 2017, available at https://wedocs.unep.org/bitstream/handle/20.500.11822/22070/EGR_2017.pdf.

2 J. Kemper, *Int. J. Greenhouse Gas Control*, 2015, **40**, 401–430.

3 C. Gough and P. Upham, *Biomass energy with carbon capture and storage (BECCS): a review*, 2010, available at http://www.tyndall.ac.uk/publications/tyndall-working-paper/2010/biomass-energy-carbon-capture-and-storage-beccs-review.

4 F. Kraxner, S. Nilsson and M. Obersteiner, *Biomass Bioenergy*, 2003, **24**, 285–296.

5 S. Fuss, J. G. Canadell, G. P. Peters, M. Tavoni, R. M. Andrew, P. Ciais, R. B. Jackson, C. D. Jones, F. Kraxner, N. Nakicenovic, C. Le Quéré, M. R. Raupach, A. Sharifi, P. Smith and Y. Yamagata, *Nat. Clim. Change*, 2014, **4**, 850–853.

This journal is © The Royal Society of Chemistry 2018

Energy Environ. Sci., 2018, **11**, 1581–1594 | **1593**

6 C. Azar, K. Lindgren, M. Obersteiner, K. Riahi, D. P. van Vuuren, K. M. J. den Elzen, K. Möllersten and E. D. Larson, *Clim. Change*, 2010, **100**, 195–202.

7 D. P. van Vuuren, S. Deetman, J. van Vliet, M. van den Berg, B. J. van Ruijven and B. Koelbl, *Clim. Change*, 2013, **118**, 15–27.

8 N. Vaughan and C. Gough, *Environ. Res. Lett.*, 2016, **11**, 095003.

9 P. Smith, S. J. Davis, F. Creutzig, S. Fuss, J. Minx, B. Gabrielle, E. Kato, R. B. Jackson, A. Cowie, E. Kriegler, D. P. van Vuuren, J. Rogelj, P. Ciais, J. Milne, J. G. Canadell, D. McCollum, G. Peters, R. Andrew, V. Krey, G. Shrestha, P. Friedlingstein, T. Gasser, A. Grubler, W. K. Heidug, M. Jonas, C. D. Jones, F. Kraxner, E. Littleton, J. Lowe, J. R. Moreira, N. Nakicenovic, M. Obersteiner, A. Patwardhan, M. Rogner, E. Rubin, A. Sharifi, A. Torvanger, Y. Yamagata, J. Edmonds and C. Yongsung, *Nat. Clim. Change*, 2016, **6**, 42–50.

10 M. Fajardy and N. Mac Dowell, *Energy Environ. Sci.*, 2017, **10**, 1389–1426.

11 K. Anderson and G. Peters, *Science*, 2016, **354**, 182–183.

12 B. E. Dale, J. E. Anderson, R. C. Brown, S. Csonka, V. H. Dale, G. Herwick, R. D. Jackson, N. Jordan, S. Ka, K. L. Kline, L. R. Lynd, C. Malmstrom, R. G. Ong, T. L. Richard, C. Taylor and M. Q. Wang, *Environ. Sci. Technol.*, 2014, **48**, 7200–7203.

13 M. Bui, M. Fajardy and N. Mac Dowell, *Appl. Energy*, 2017, **195**, 289–302.

14 P. Moriarty and D. Honnery, *AIMS Energy*, 2016, **5**, 20–38.

15 C. Hall, S. Balogh and D. Murphy, *Energies*, 2009, **2**, 25–47.

16 D. J. Murphy, C. A. S. Hall, M. Dale and C. Cleveland, *Sustainability*, 2011, **3**, 1888–1907.

17 M. Raugei, P. Fullana-i Palmer and V. Fthenakis, *Energy Policy*, 2012, **45**, 576–582.

18 A. L. Stephenson and D. J. MacKay, *Life Cycle Impacts of Biomass Electricity in 2020*, Department of Energy and Climate Change technical report, 2014.

19 M. Dale and S. M. Benson, *Environ. Sci. Technol.*, 2013, **47**, 3482–3489.

20 C. A. S. Hall, J. G. Lambert and S. B. Balogh, *Energy Policy*, 2014, **64**, 141–152.

21 G. G. T. Camargo, M. R. Ryan and T. L. Richard, *BioScience*, 2013, **63**, 263–273.

22 A. Grzybek, *Modelling of biomass utilisation for energy purpose*, 2010.

23 I. Lewandowski, A. Kicherer and P. Vonier, *Biomass Bioenergy*, 1995, **8**, 81–90.

24 F. Murphy, G. Devlin and K. McDonnell, *Renewable Sustainable Energy Rev.*, 2013, **23**, 412–420.

25 B. Kalita, PhD thesis, University of Guelph, 2012.

26 X. Lu, M. R. Withers, N. Seifkar, R. P. Field, S. R. H. Barrett and H. J. Herzog, *Bioresour. Technol.*, 2015, **183**, 1–9.

27 X. Qin, T. Mohan, M. El-Halwagi, G. Cornforth and B. A. McCarl, *Clean Technol. Environ. Policy*, 2006, **8**, 233–249.

28 P. Börjesson, *Biomass Bioenergy*, 1996, **11**, 305–318.

29 S. Njakou Djomo, O. El Kasmioui, T. De Groote, L. S. Broeckx, M. S. Verlinden, G. Berhongaray, R. Fichot, D. Zona, S. Y. Dillen, J. S. King, I. A. Janssens and R. Ceulemans, *Appl. Energy*, 2013, **111**, 862–870.

30 R. Ehrig, PhD thesis, Technical University (TU) Berlin, 2014.

31 V. Forgie and R. Andrew, *Life Cycle Assessment of Using Straw to Produce Industrial Energy in New Zealand*, Landcare research and new zealand centre for ecological economics technical report, 2008.

32 M. Elsayed, R. Matthews and N. Mortimer, *Carbon and energy balances for a range of biofuels options*, Resources Research Unit, Sheffield Hallam University technical report, 2003.

33 *CCC, UK climate change following the Paris Agreement*, Committee on Climate Change technical report, 2016.

34 EURELECTRIC, *Efficiency in Electricity Generation*, 2003, available at http://dx.doi.org/10.1016/j.watres.2009.01.036.

35 IEA, *Energy Efficiency Indicators for Public Electricity Production from Fossil Fuels*, 2008, available at https://www.iea.org/publications/freepublications/publication/En_Efficiency_Indicators.pdf.

36 DRAX GROUP plc, *Drax annual report and accounts: A reliable, renewable future, today the way in the generation*, 2015, available at http://asp-gb.secure-zone.net/v2/index.jsp?id=666/3685/10863&lng=en.

37 The UK 2050 Calculator, DECC, http://2050-calculator-tool.decc.gov.uk/#/home, accessed 2017.

38 FAOSTAT, http://www.fao.org/faostat/en/#home, accessed 2017.

39 Digest of UK Energy Statistics (DUKES), *Renewable sources of energy*, 2017, available at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/633782/Chapter_6.pdf.

40 N. M. Dowell and M. Fajardy, *Environ. Res. Lett.*, 2017, **12**, 045004.

41 R. Baciocchi, G. Storti and M. Mazzotti, *Chem. Eng. Process.*, 2006, **45**, 1047–1058.

42 M. Ranjan and H. J. Herzog, *Energy Procedia*, 2011, **4**, 2869–2876.

43 K. S. Lackner, *Energy*, 2013, **50**, 38–46.

44 A. Moro and L. Lonza, *Transportation Research Part D: Transport and Environment*, 2017.

45 Ecometrica, *Electricity-specific emission factors for grid electricity*, available at https://ecometrica.com/assets/Electricity-specific-emission-factors-for-grid-electricity.pdf.